A Stranger in a Strange Land

Physicist Tales from the World of Neuroscience

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P-21

Outline

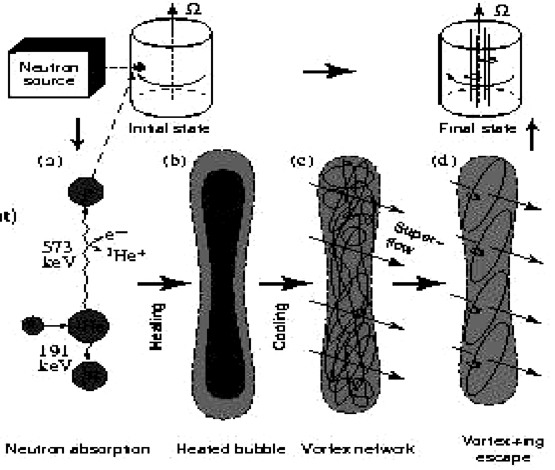
I. Introduction and Motivation
II. General Discussion of Neural Systems and their Properties
III. Oscillations in the Retina
IV. Conclusions

Theoretical Physics
to Computational Neuroscience

COSMIC STRINGS IN THE
EARLY UNIVERSE

CONDENSED MATTER
EXPERIMENTS

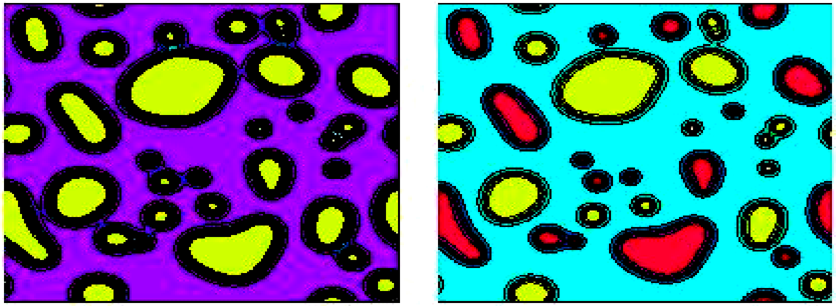
Superfluid He–3 (right)
Liquid Crystals
Superconductors
Superfluid He–4
Bose–Einstein
Condensates



PHASE TRANSITIONS
AND THE FORMATION OF TOPOLOGICAL DEFECTS

DIVERSE APPLICATIONS: FROM
PARTICLE PHYSICS TO MATERIALS
SCIENCE

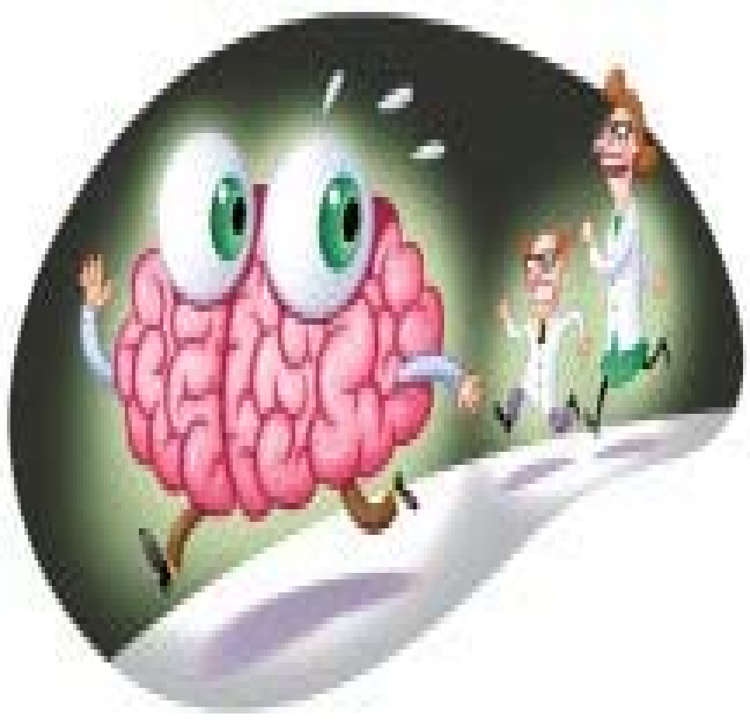
NONEQUILIBRIUM AND NONLINEAR:
LARGE–SCALE NUMERICAL SIMULATIONS
ARE AN IMPORTANT TOOL IN THE STUDY
OF THESE COMPLEX SYSTEMS



MAGNETIC FLUX VORTICES IN SUPERCONDUCTORS

Order Parameter (left) and Magnetic Flux (right)
After a Quench in a 2D Type–I Superconductor

Why Neuroscience?
(a personal perspective)



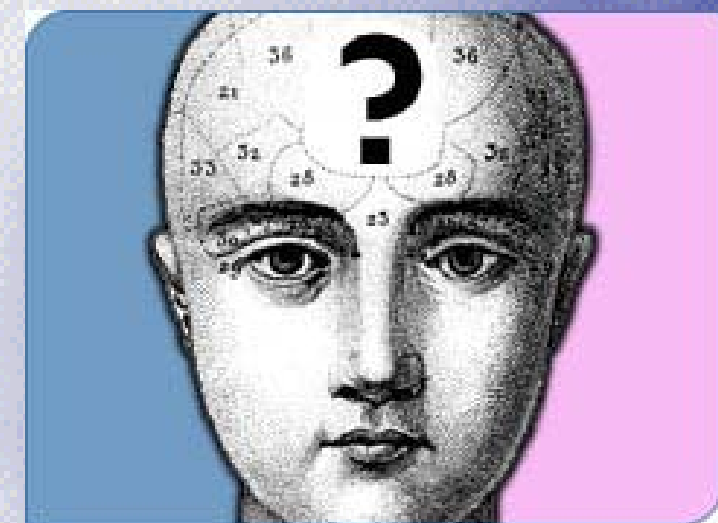
- One of the most challenging pursuits in science is the attempt to comprehend the complex functioning of the human brain
- 100 billion neurons, highly connected networks, **NO** good ideas as to how it all works
- Nothing could be more fundamental than *understanding how we understand.*
- Machine intelligence is inevitable (might as well get a head start!)
- It’s fun!

Why Neuroscience?
(A pragmatic perspective)

- Neural systems solve certain classes of problems better then anything we can create
- They solve problems quickly (tens of milliseconds for a behavioral response) and efficiently
- They are tremendously adaptive and can deal with complex and dynamic situations
- We would like to be able to design similarly powerful systems with diverse applications from autonomous robots and visual recognition systems to neural prosthetics

The really really important question...

Why are we *aware (conscious)* of what the brain does?



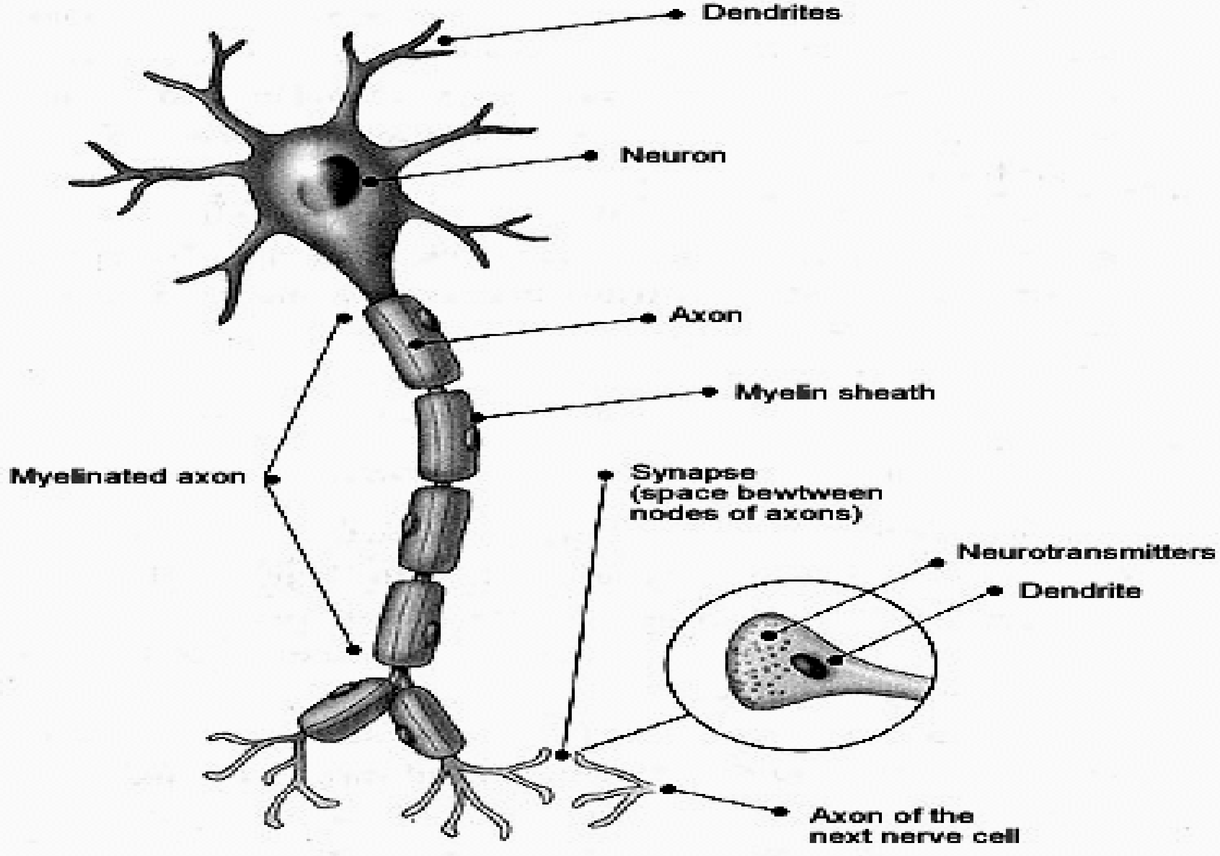
Hard (but not impossible)!

No Mysterians Allowed!

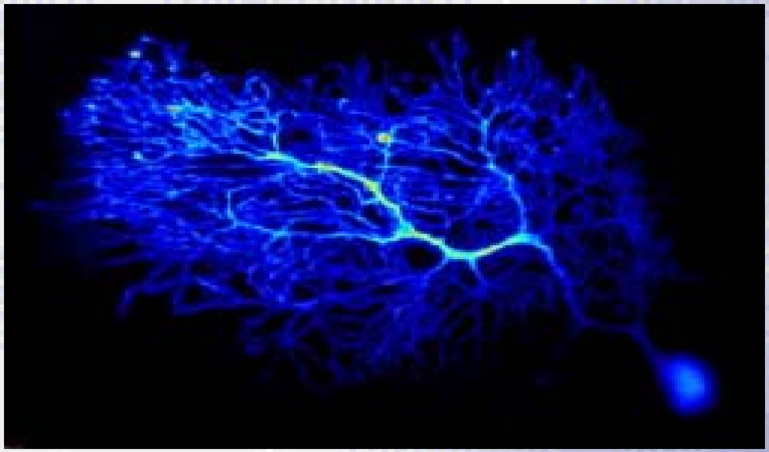
How Does The Brain Represent And Interact With The World ?

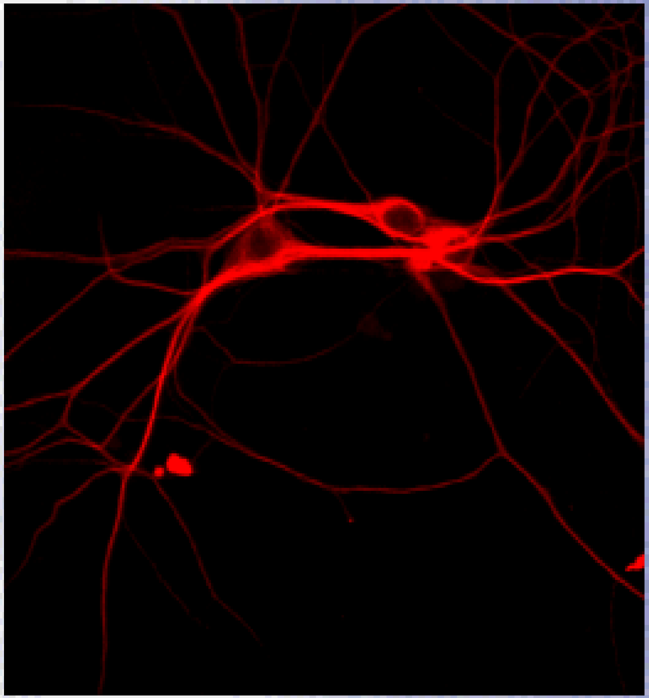
- What is the nature of the neural code(s)? (average activity or precise timing, correlated or independent…)
- How do we analyze the complex function of biological neural networks? (global attractors, dynamical systems, network theory…)
- What principles unify the complex and diverse behaviour of neural systems?

Neurons: Basic Units of the Nervous System



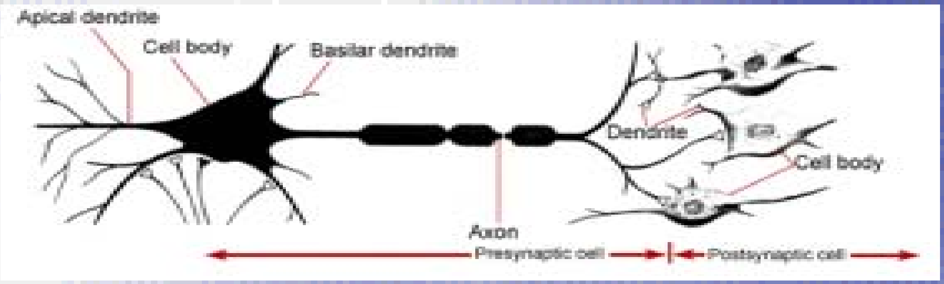
A neuron, complete with axon, dendrites, and synapses.

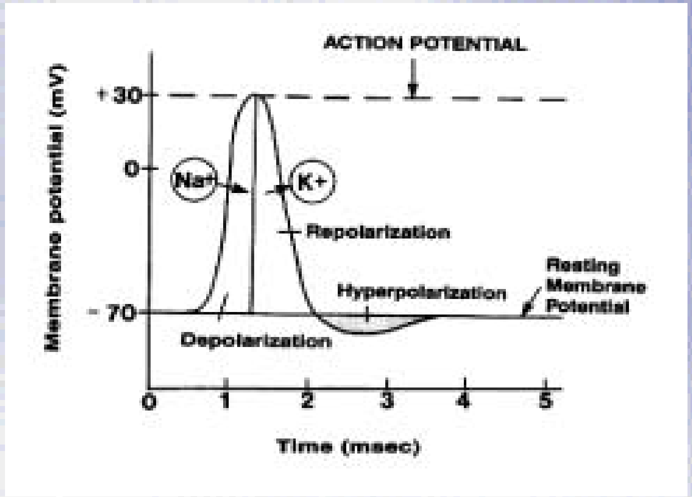


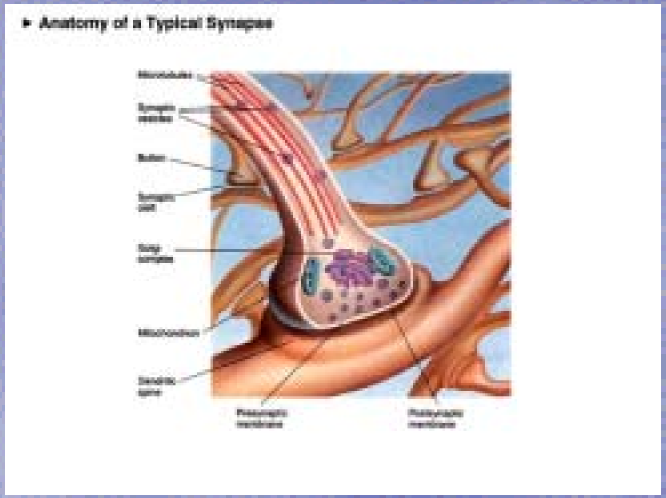


Neuron Signaling

Neurons communicate by stereotypical electrical signals (action potentials or spikes)

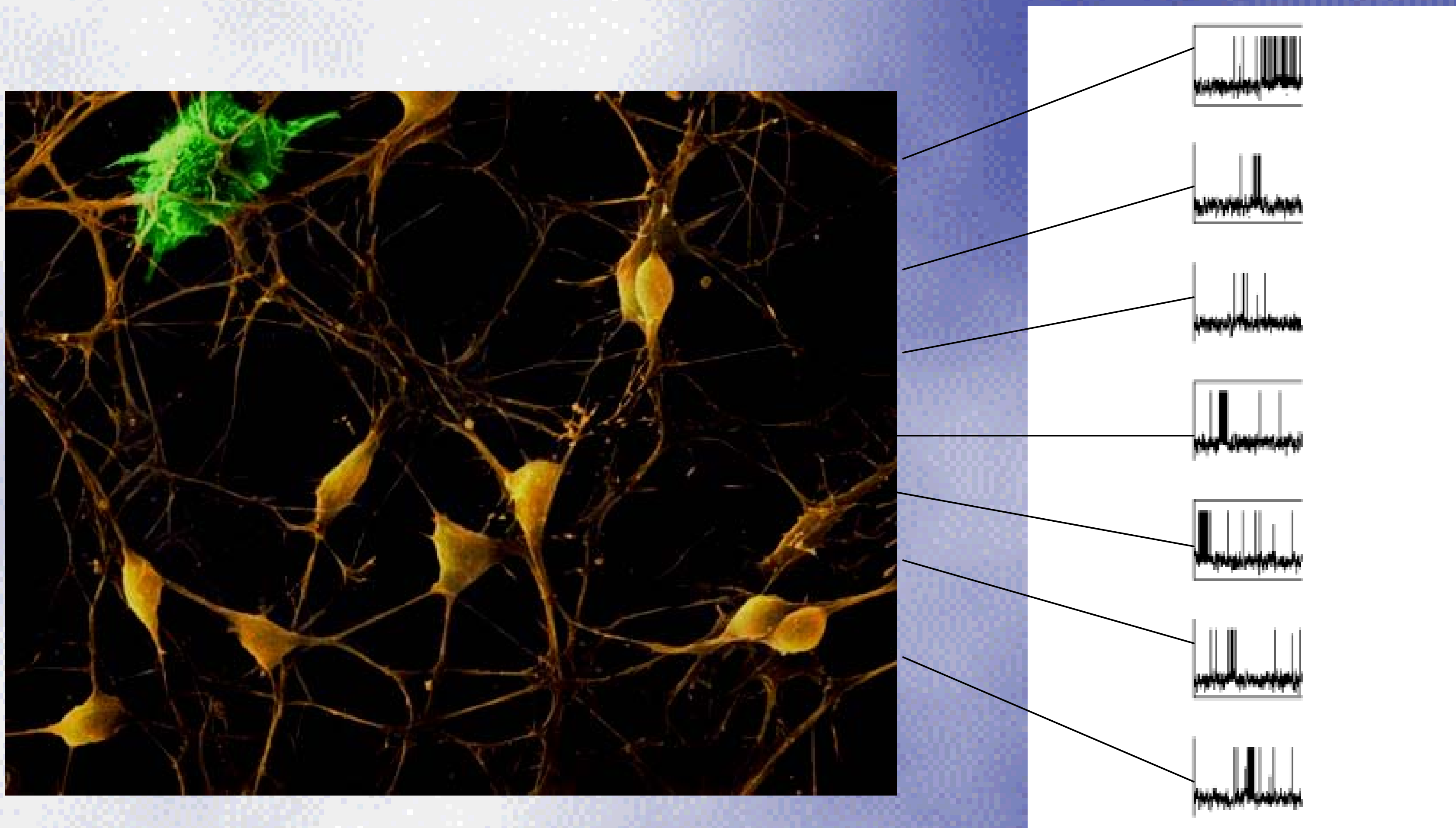






Spikes are the basis of a universal neural language and are the only signals transmitted over long distances

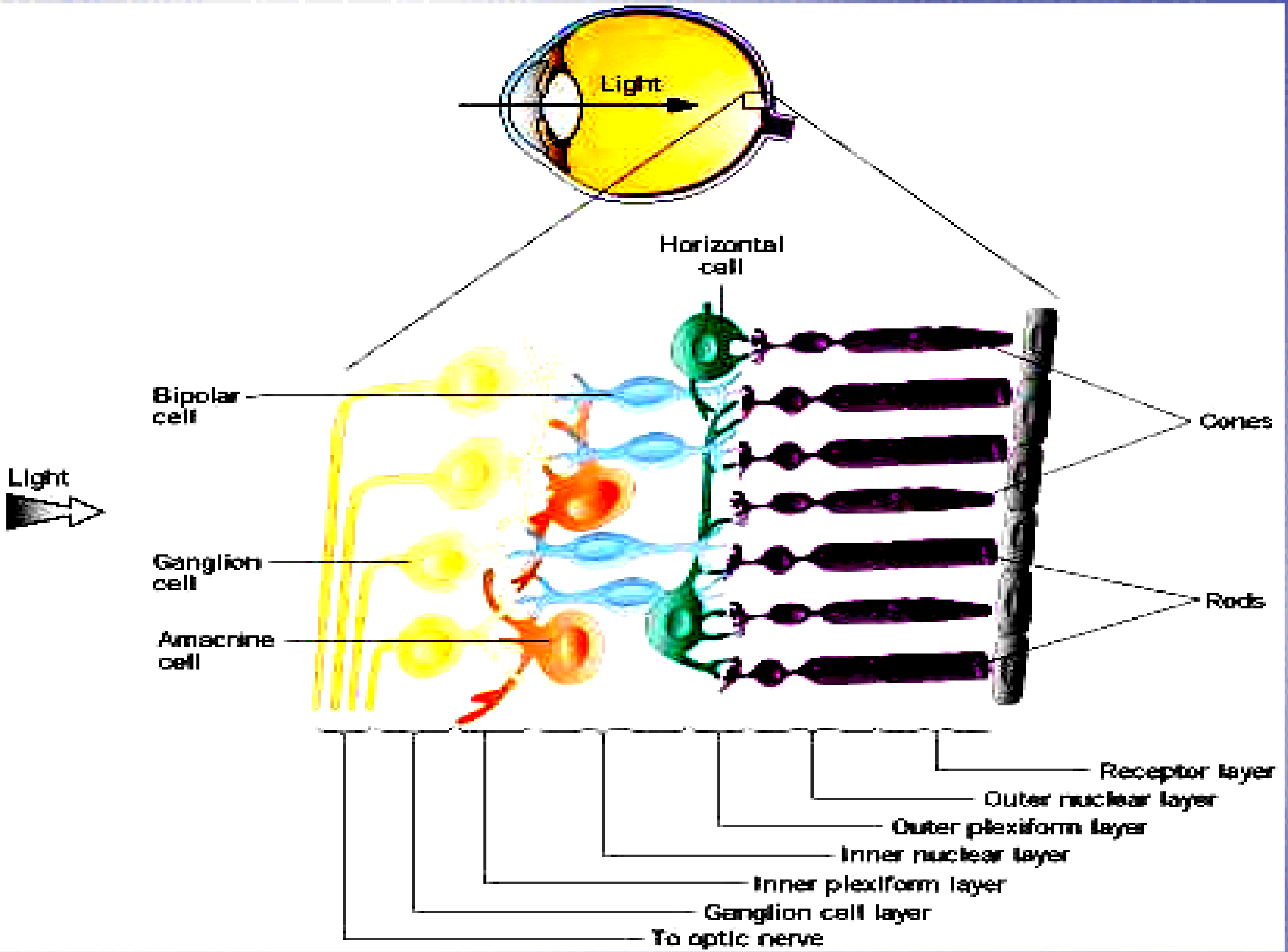
A Central Problem in Neuroscience: How to make sense of spike patterns



General Approaches

- Information Theory (*where is the information*)
  What spike pattern carries the most information about the stimulus
- Reverse Correlation (*what is the information*)
  Identify aspects of the stimuli that drive neurons and neural networks
- Modeling (*where, what and why is the information*) How do we understand the design of a neural system

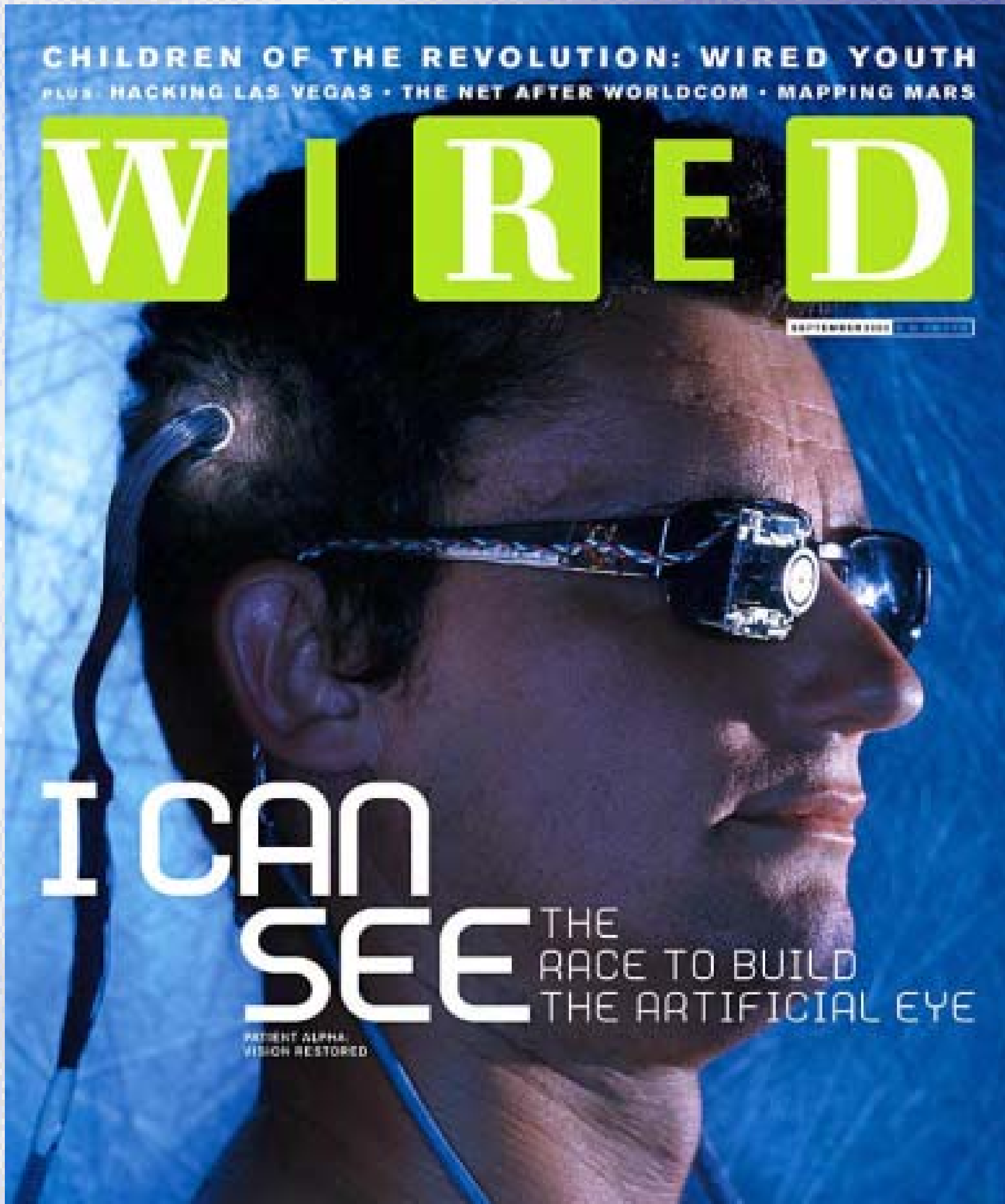
The Retina



Light
Horizontal cell
Bipolar cell
Cones
Light
Ganglion cell
Rods
Amacrine cell
Receptor layer
Outer nuclear layer
Outer plexiform layer
Inner nuclear layer
Inner plexiform layer
Ganglion cell layer
To optic nerve

The Retina as a Model Neural System

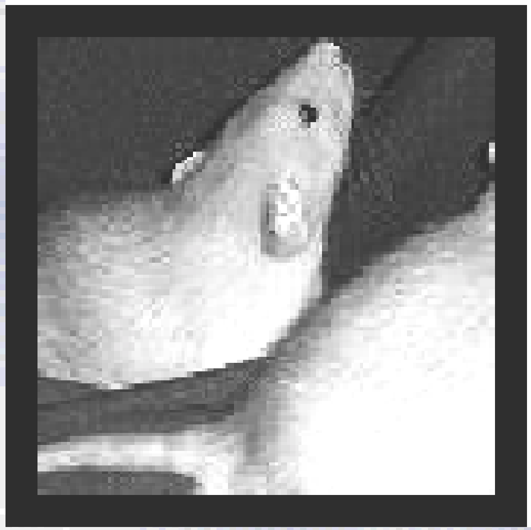
- Can be studied as an intact and isolated neural system with well-defined input (visual world) and output (ganglion cell spike-trains)
- No feedback connections from the brain
- Known network anatomy (cell types and connections)
- Ideal system for studying the neural code (if universal principles exist they might be evident here)
- Retinal prosthetic (return for a talk by Mark Humyan from USC)


CHILDREN OF THE REVOLUTION: WIRED YOUTH
PLUS: HACKING LAS VEGAS • THE NET AFTER WORLDCOM • MAPPING MARS
WIRED
I CAN SEE
THE RACE TO BUILD THE ARTIFICIAL EYE
PATIENT ALPHA: VISION RESTORED

What Does the Eye Tell the Brain?

(if you could decode the optic nerve, what would the world look like?)

Spike Rate Encodes Pixel Intensity



Input Image

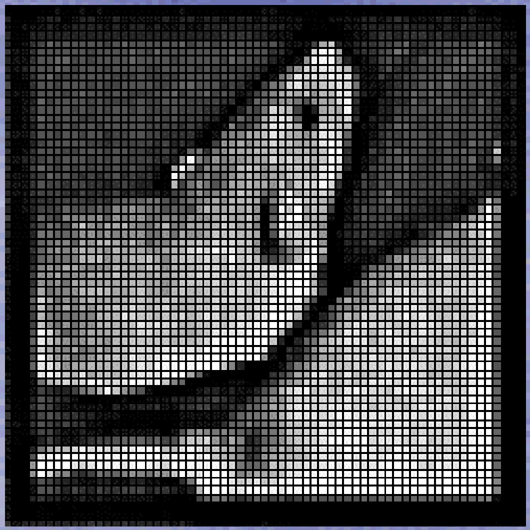
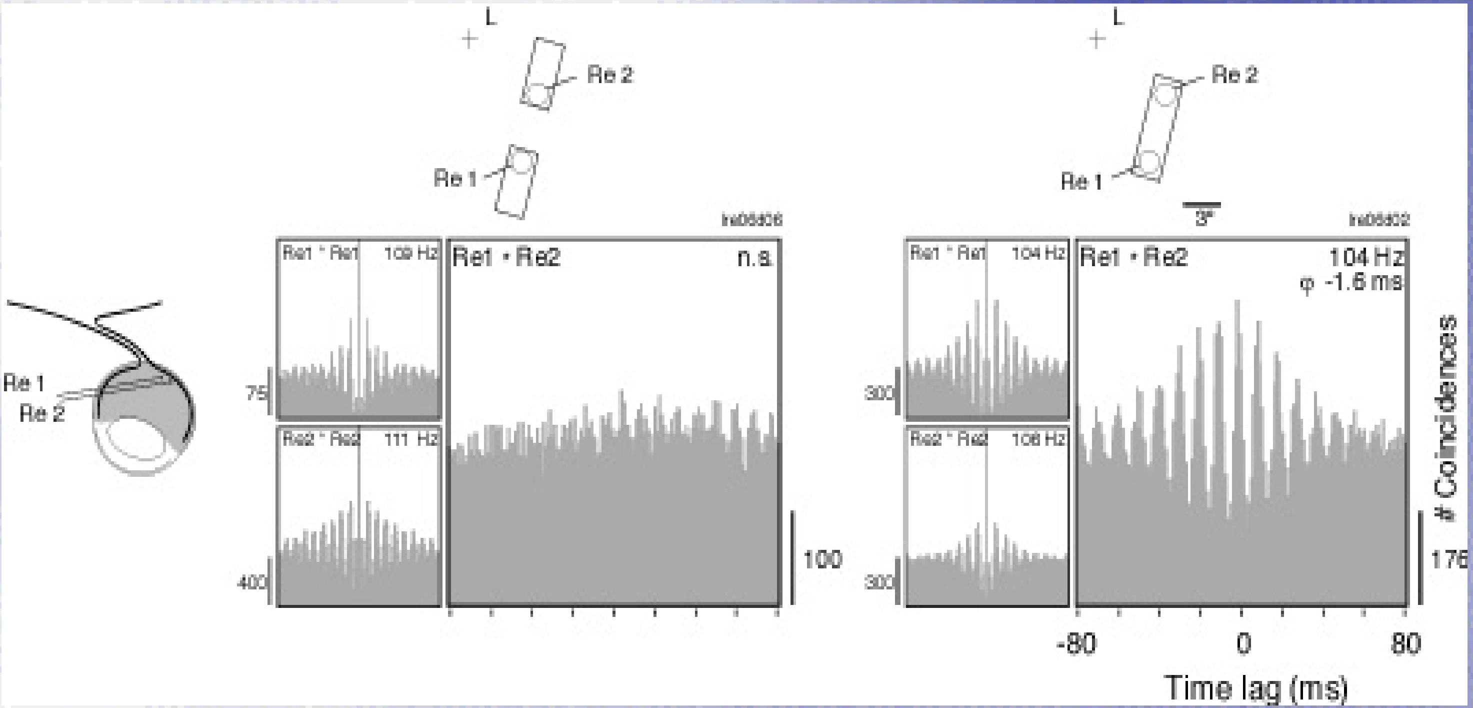


Image Reconstruction Based on Spike Rates

But is spike rate the entire story…

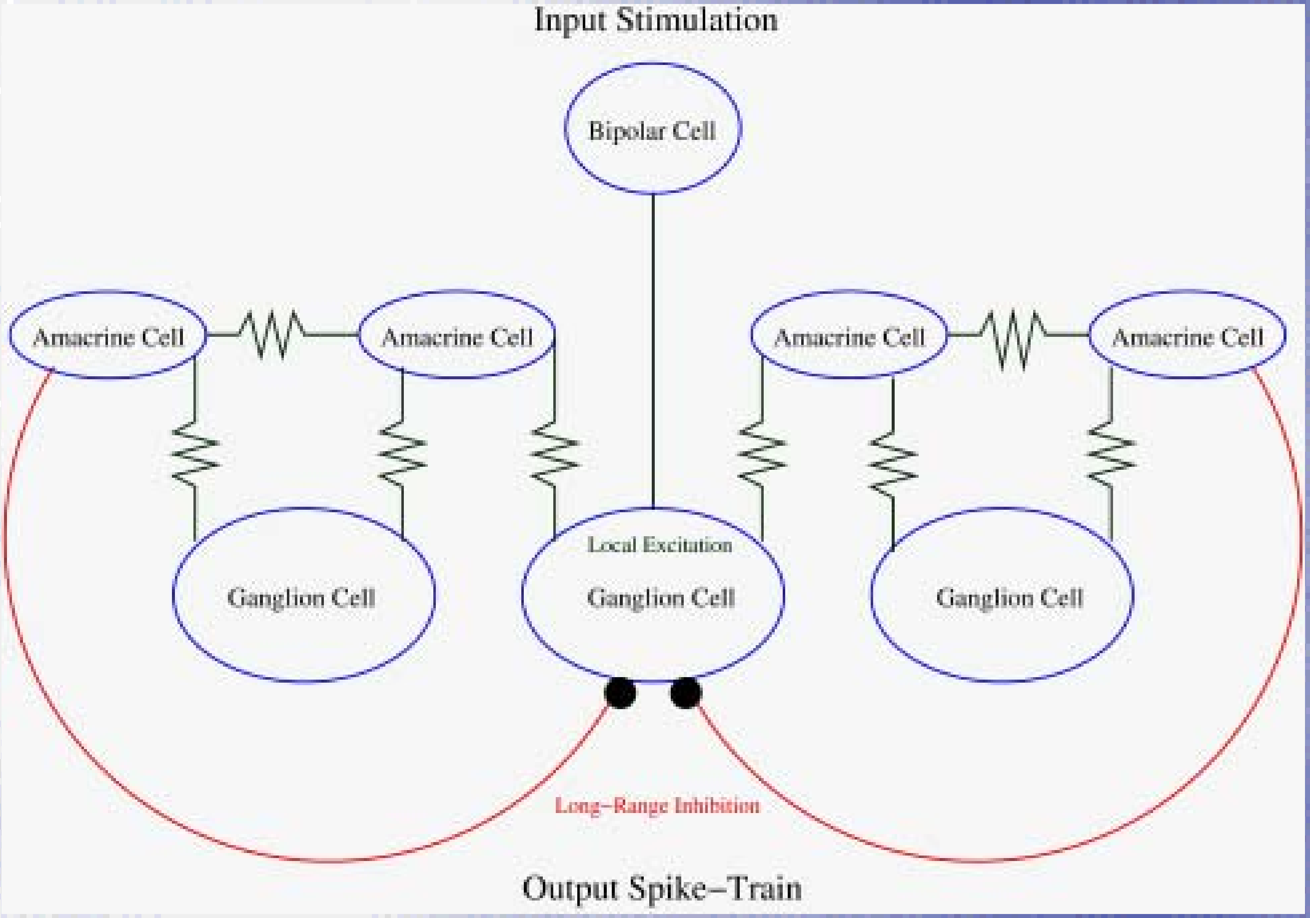
Ganglion cell spike-trains also oscillate



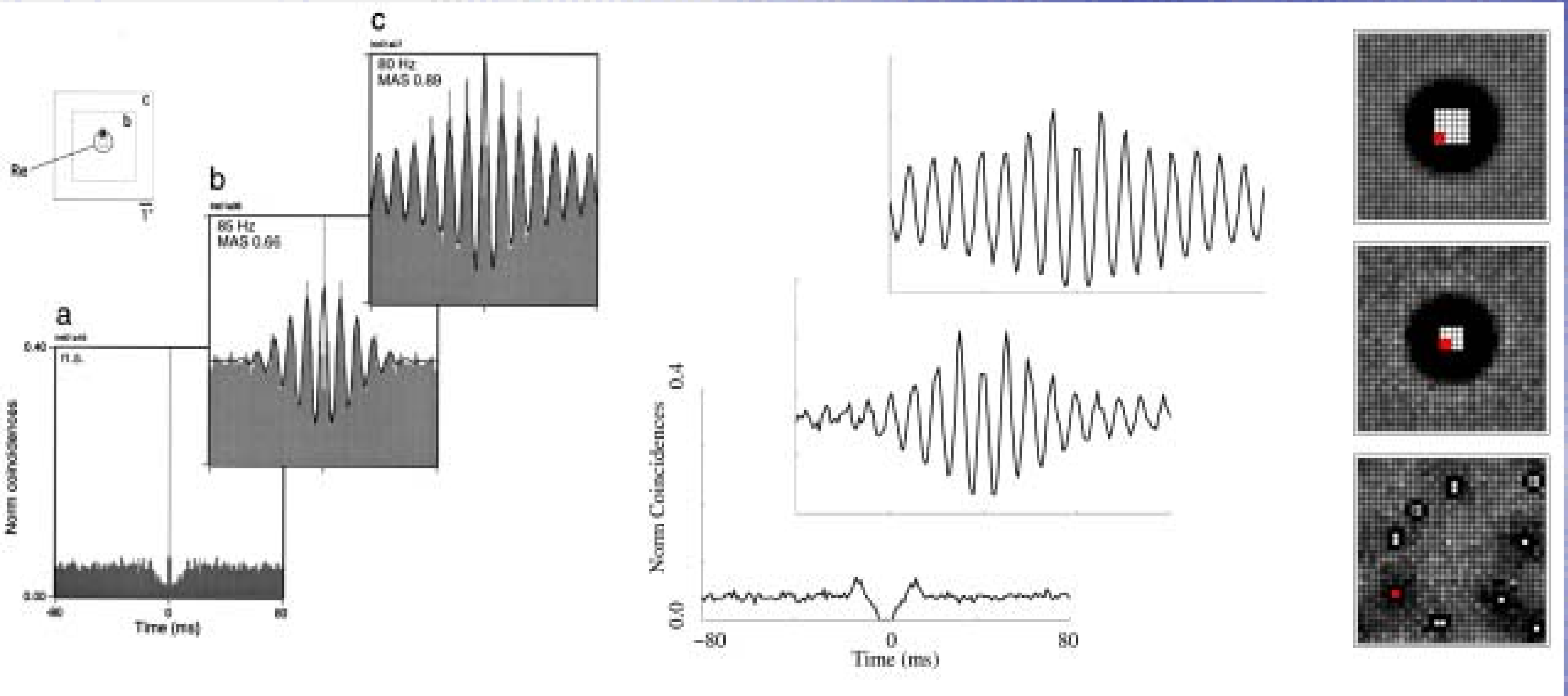
Neuenschwander and Singer, *Nature* (1996)

What could oscillations mean?

A Model of
Retinal Oscillations
(G. Kenyon and collaborators)



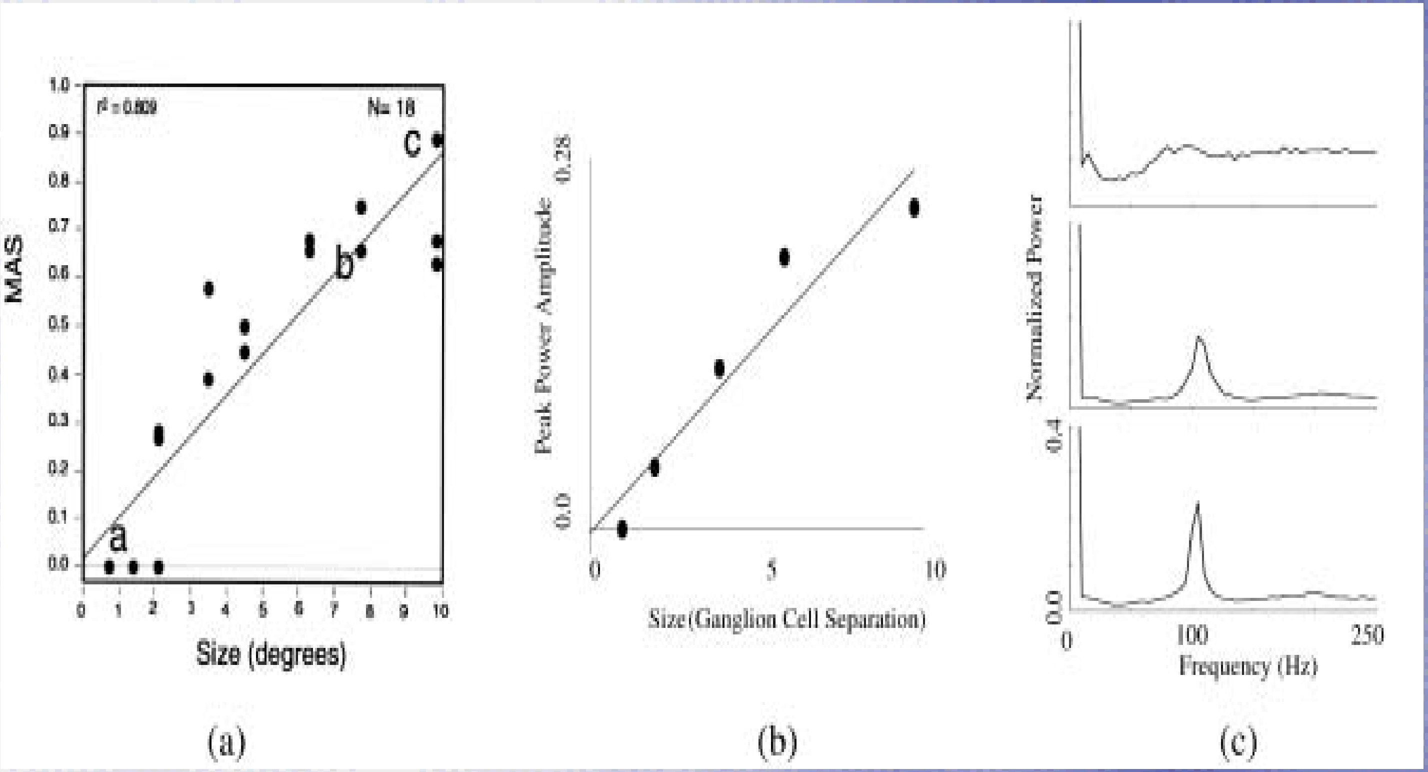
Synchronous and Oscillatory Behavior of Model Spike Trains Matches Experiment



(a) (b) (c)

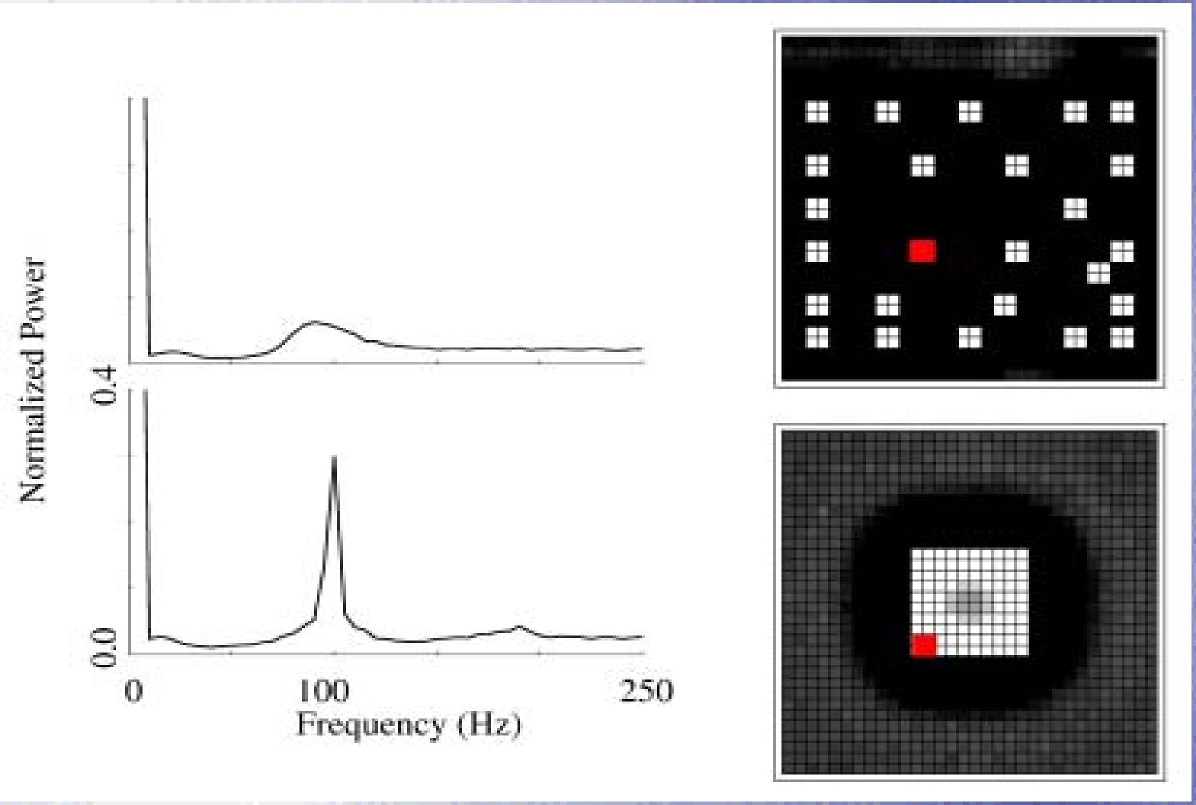
(a) Neunschwander et. al., *Vision Research* (1999)

Oscillations Scale Linearly with Stimulus Size



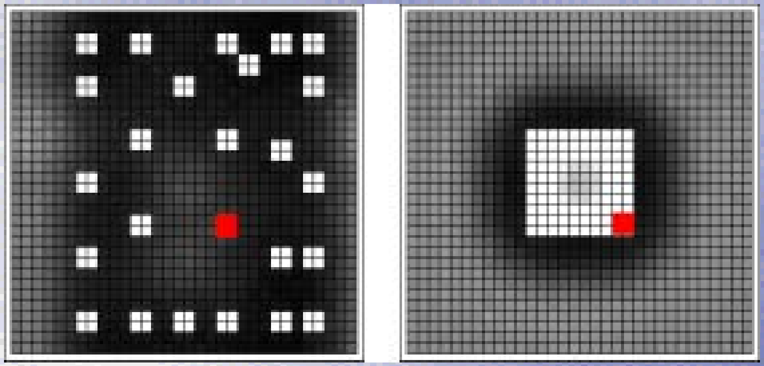
(a) Neunschwander et. al., *Vision Research* (1999)

Oscillations Depend on Contiguity Not Total Retinal Illumination

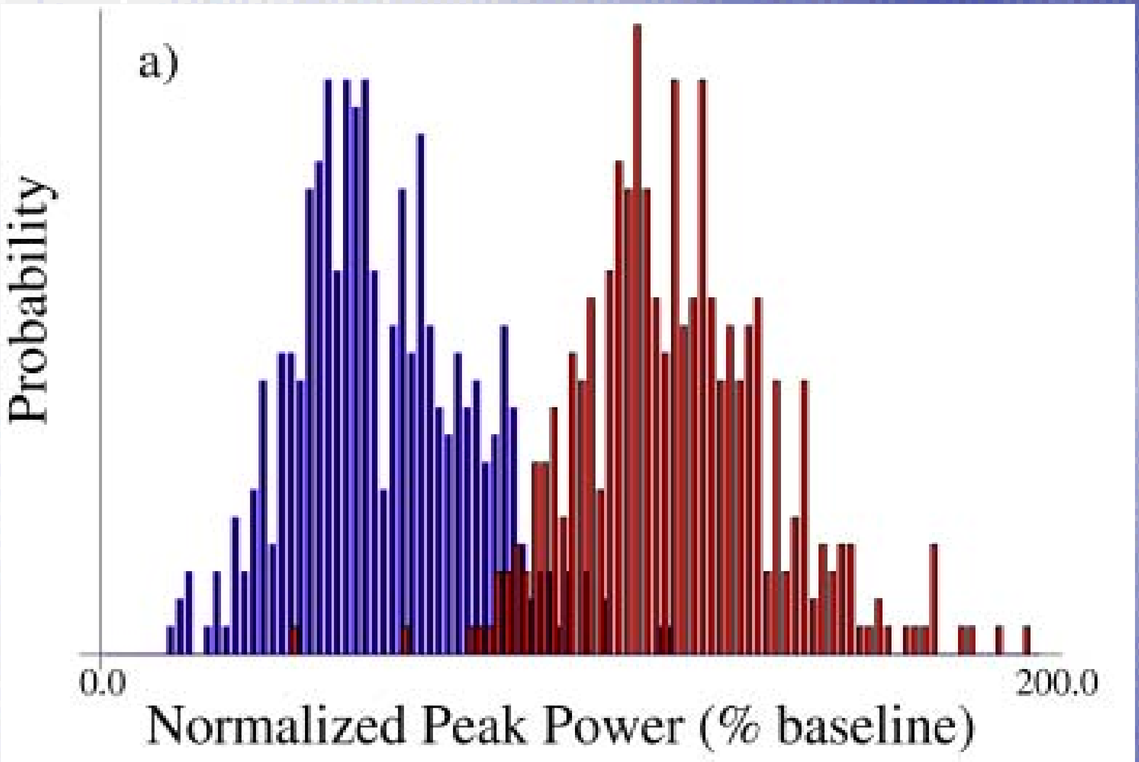


Is Oscillatory Information Reasonably Available to Downstream Neurons?

- Single Stimulus Presentation
- Biological Time Scales (20ms for earliest evoked response to 200ms for perceptual judgments)
- Small Neural Population (hints at processing)

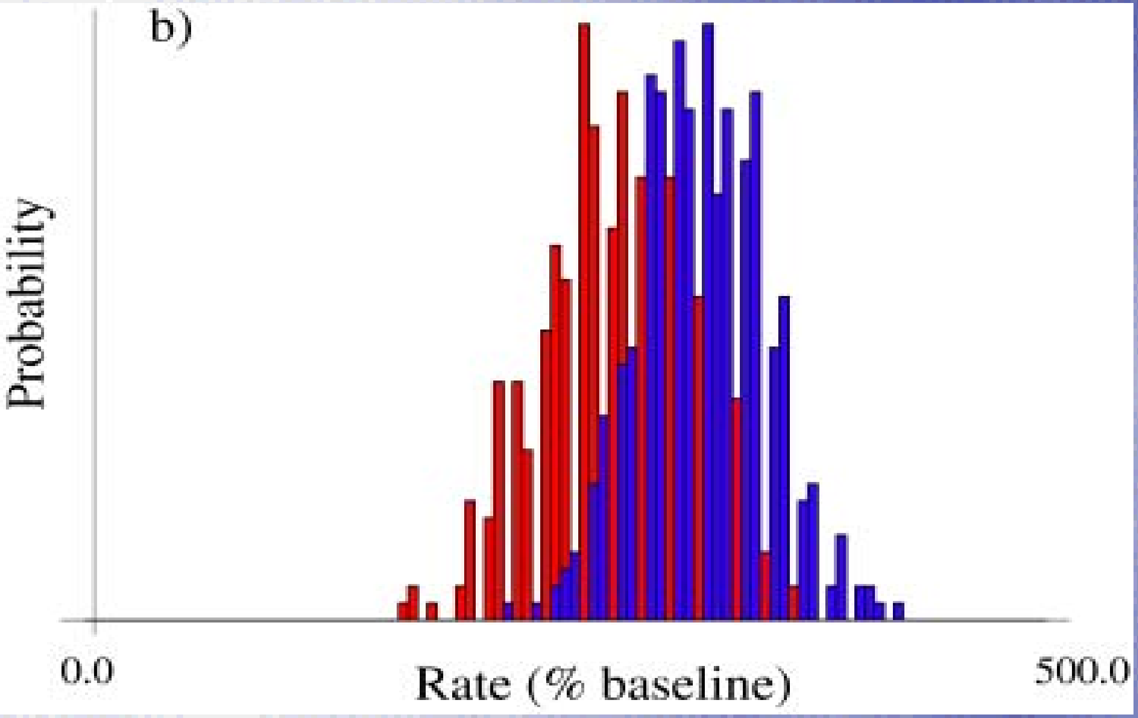


Oscillations Locally Discriminate Contiguous and Fragmented Stimuli on Single-Trials

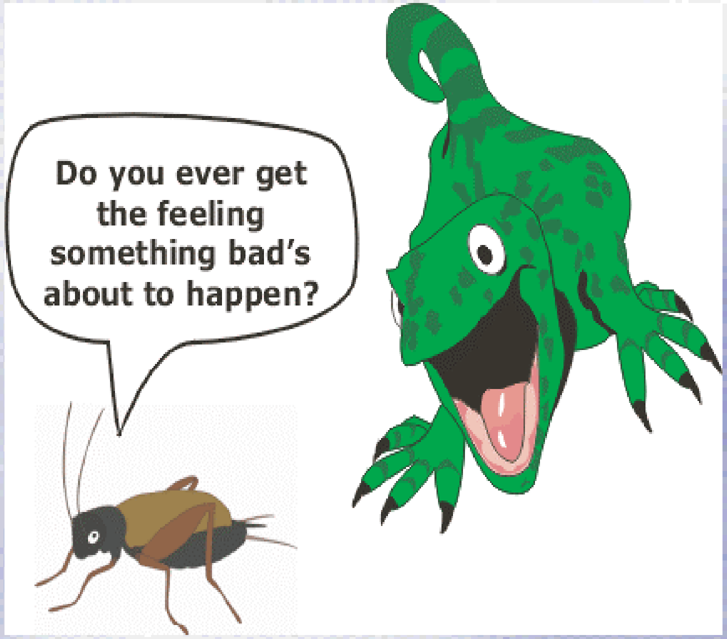


…on the other hand

spike rate is a poor (local) discriminator



Are Retinal Oscillations Exploited by the Brain?



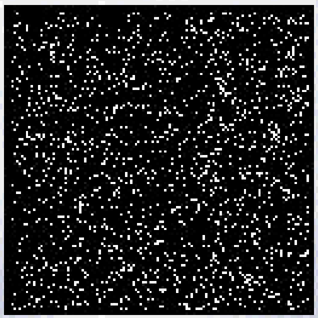
- Are downstream neural systems sensitive to oscillatory input?
- Does removing oscillations produce measurable behavioural deficiency?
- Do oscillations in other brain regions signify similar encoding?

A definitive demonstration of the functional role of synchronous oscillations remains undone

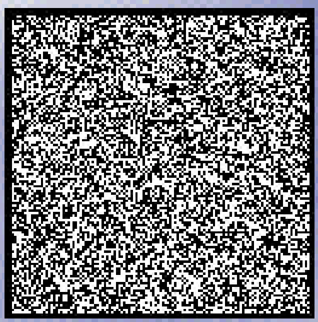
Oscillations Summary

- Using a computational model of the retina, we have shown that information about the presence of large objects is available locally to downstream neural systems on behavioural time-scales.
- In our analysis we went beyond the *characterization* of retinal spike-trains and asked whether oscillatory information is available to downstream neurons in a reasonable manner.
- Necessary but not sufficient condition for the use of retinal oscillations by the early visual processing regions of the brain .

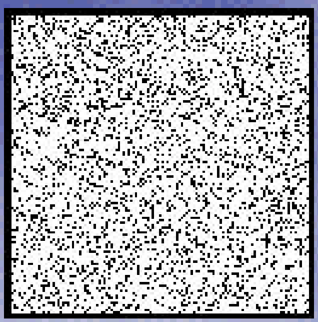
A Percolation Phase Transition in the Retina?



P=0.1



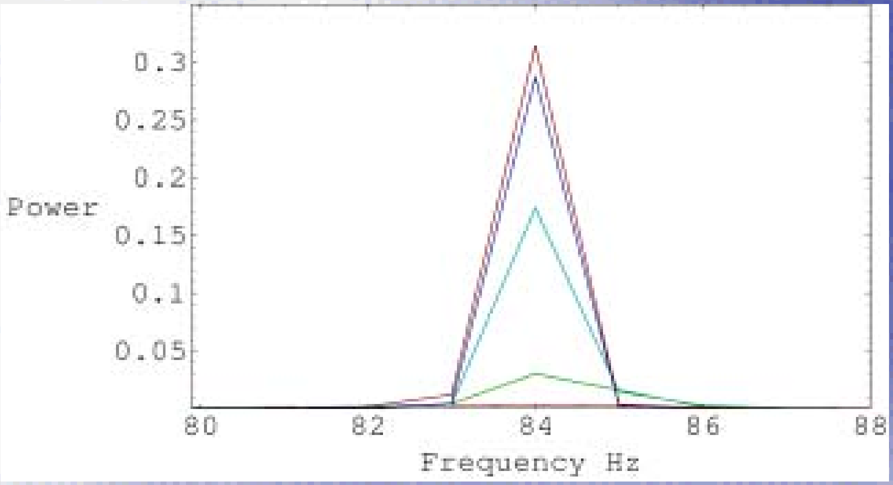
P=0.5

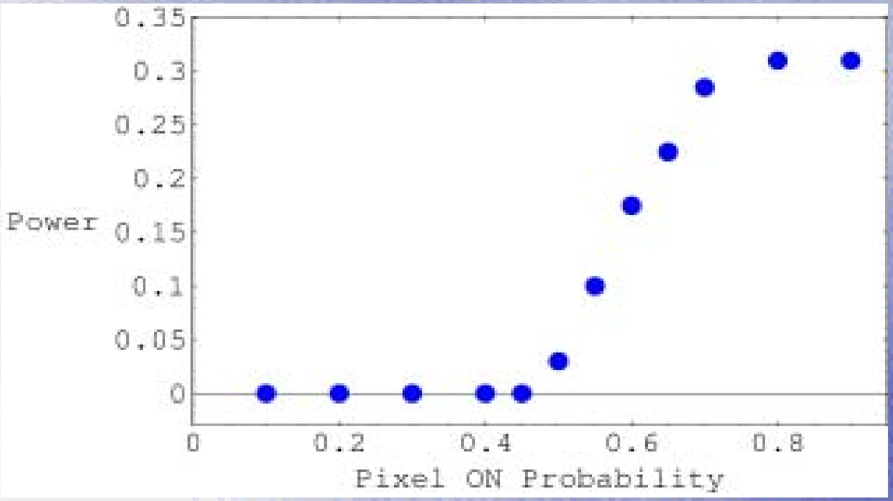


P=0.8

P=Pixel ON Probability

Normalized Power Spectrum Summed from all Cells in Model Retina





Conclusions

- We explored the possible encoding roles of synchronous oscillations in the retina and found that oscillations may provide a local neural label, signalling that the responding cell is part of a larger visual feature.
- We identified a possible phase transition in the output spike-trains of the retina. We have shown that a percolation phase transition in the input image is accompanied by an abrupt change in the average power of our model retina.
- Neural systems, rich in complexity and relevance, provide a challenging and exciting arena in which to apply the techniques and philosophies of physics. Physics and Neuroscience both greatly benefit from this cross-fertilization.

Acknowledgments

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